SATS: SMALL, AUTOMATED TRACKING SYSTEM -- ELEMENTS OF A BETTER SYSTEM FOR SATELLITE TRACKING AND TELEMETRY

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ABSTRACT

The Jet Propulsion Laboratory (JPL) has been exploring applications of precise Global Positioning System (GPS) techniques to navigation and data communication for Earth orbiting spacecraft. GPS tracking can be exploited in several different ways, depending on the orbital altitude of the spacecraft of interest, to support orbit and trajectory determination. At low-Earth orbits below 3000 km, "upwards-looking" GPS tracking analogous to ground-based GPS tracking can be used to provide real-time orbit determination for navigation. For these applications, GPS flight receiver architectural studies coupled with advances in GPS data analysis and estimation techniques at JPL have resulted in a wide range of GPS-based navigation capabilities that trade off orbit accuracy for instrument complexity and cost. Orbit accuracies of 500 meters (ultra low power architecture) down to 10 meters can be routinely achieved in real-time with a properly equipped, stand-alone flight receiver. Much higher accuracies can be achieved in a post-processing mode when data from a global ground network of precise GPS receivers are differentially combined with the flight receiver data. This technique has already been demonstrated at JPL, where orbits accurate to better than a few cm in height are generated automatically for the TOPEX/Poseidon spacecraft. In addition, a GPS flight receiver architecture that integrates the command telemetry receive function is being explored and shows significant cost savings potential. At Earth orbiting altitudes between 3000 km and 8000 km, visibility of GPS rapidly decreases and it becomes advantageous to add a nadir pointing antenna in order to continuously see enough GPS signals to navigate an orbiter. For orbits above 8000 km, JPL has developed the GPS-like tracking (GLT) technique which dispenses with the on-board GPS receiver in favor of transmitting beacon (usually the existing spacecraft-to-ground link (SGL)) whose phase is tracked, simultaneously with normal GPS signals, by a ground network of "enhanced" GPS receivers. With the GPS data providing several key calibration parameters, the SGL phase data can be processed in near real-time to produce spacecraft orbits with accuracies of a few tens of meters up to geosynchronous orbits (36000 km) and beyond. A recent JPL experiment demonstrated that the GLT approach can be used to determine the orbits of NASA's geostationary Tracking and Data Relay Satellites (TDRS) to better than 25 meters. The systems referred to above all have the potential to provide inexpensive and autonomous navigation/orbit production and, in some cases, integrated data communications for a wide class of Earth orbiters and should be of interest to designers of NASA, military, and commercial space systems.

INTRODUCTION

GPS satellites (presently numbering 25) transmit carrier signals at 1.228 and 1.575 GHz (L-band) which are modulated by pseudo random noise (PRN) ranging codes as well as a navigation message with GPS clock and orbit information necessary for real-time positioning. In normal operation, the Department of Defense (DOD) turns on *selective availability* (SA) for most GPS satellites, introducing a clock dither and adding errors to the broadcast ephemeris, as well as *anti-spoofing* (AS), which encrypts the precise ranging codes (P-code). Authorized users can be equipped with GPS receivers which accept keys to correct for these effects yielding about 10 meter stand-alone positioning accuracy, but other users see only 50-100 meter accuracy.

Civilian and scientific uses of GPS have led to a wide variety of applications in geodesy, surveying, navigation, and remote sensing, and resulted in the development of sophisticated strategies which enable accuracies much greater than 50-100 meter. Examples include a cm-level non-real time positioning capability for receivers on the surface of the Earth [1], several-cm accuracy for low-Earth satellite orbit determination [2], and, in theory, several-meter accuracy for high-Earth orbiters [3]. Such high-precision applications typically require a global GPS ground network of high quality dual-band receivers and simultaneous post processing of data in estimation software which incorporates detailed physical and observation models.

JPL is developing several candidate technologies in the areas of GPS receiver hardware and data analysis software that are suitable for either direct transfer to industry or further co-development with commercial partners. These technologies are based on JPL-developed high precision, configurable GPS receiver architectures and automated, highly flexible, GPS-based multiparameter estimation algorithms that have been adapted and streamlined specifically for Earth orbiter trajectory and orbit determination and data communications. This paper will present these technologies, some of which have been demonstrated in the field while others are still in the conceptual stage, as they apply to Earth orbiting spacecraft at various altitudes.

.OW EARTH ORBITER TECHNOLOGIES

Most military and civilian ground-based GPS applications involve an upward-looking geometry where the users' receiving antennas are pointed away from the Earth towards the GPS satellites. This geometry is depicted in Figure 1, which shows the low-Earth orbiter TOPEX/Poseidon and a global network of ground stations tracking GPS satellites.

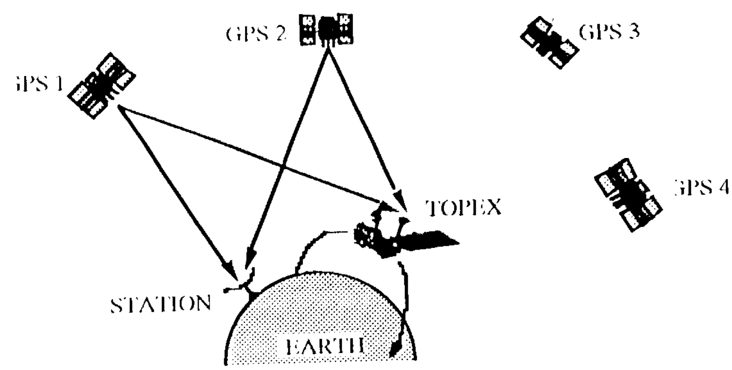


Figure 1. Upwards looking geometry for low-Earth orbiter and ground stations tracking GPS.

TOPEX/Poseidon, a joint NASA/CNES spacecraft operated by JPL, carries a radar altimeter to map the oceans' surfaces and measure global ocean circulation. The satellite also carries a flight qualified GPS receiver to demonstrate GPS-based spacecraft orbit determination. At its altitude of 1340 km, 6 to 8 GPS satellites are typically visible at a given time with a zenith-pointing, hemispherical field of view antenna. By relying at least partially on available precise force models, a dynamical fit can be performed in a sequential filter using only GPS flight data over at least several hours. The accuracy of the resulting solution (a few tens of meters) improves significantly over that achieved from geometric solutions (50 to 100 meters). Additional accuracy improvement results from differential cancellation of the receiver and transmitter clock errors (and SA clock dither) at each measurement epoch when the ground and flight receiver data are processed together. This requires common visibility of at least two GPS in the flight receiver and a ground receiver (see Figure 1). When all the GPS orbits are estimated as well, low-Earth orbit determination at the few cm-level (2-3 cm RMS, radial component, ~10 cm RMS in cross track and along track components) was demonstrated by JPL for the TOPEX/Poseidon spacecraft [2] when about 15 ground sites were used.

The data analysis software being used for the above demonstration was developed at JPL and is an adaptation of the GIPSY/OASIS II package of modeling and estimation algorithms [2]. The ground network of 15 stations consists of geodetic quality dual-frequency receivers [4,5] which can utilize the P-code when not encrypted, or rely on codeless techniques to recover precise ionospherically corrected observables when AS encryption is on. The GPS receiver used to collect the TOPEX/Poseidon flight data is also a dual-frequency P-code receiver, but with moderate performance and relatively high mass and power consumption specifications [6]. In contrast to the ground stations, the TOPEX/Poseidon flight receiver reverts to L1-C/A tracking when the P-code is encrypted. The next few sections will examine more closely, and consider future improvements to, the data analysis strategies, ground network design, and flight receiver design as they apply to orbit and trajectory determination for low-Earth orbiters.

Data Analysis Strategies and Implementation

The GPS data collected by TOPEX/Poseidon are routinely processed in an automated fashion with GIPSY/OASIS II analysis software using a technique known as reduced dynamic tracking. The reduced dynamic strategy exploits the extraordinary geometric strength of GPS to minimize the dependence on dynamic force models and achieve a superior orbit solution through an optimal synthesis of dynamic and geometric information [2]. Other (ground-based) techniques against which the GPS-based orbits were compared, in contrast, provide measurements in just one direction at a time and may have substantial coverage gaps; they must therefore rely on models of the satellite trajectories (derived from dynamic force models) to recover three-dimensional information.

The accuracy of GPS-based reduced dynamic orbit solutions were assessed using three approaches: 1) internal consistency checks within the GIPSY/OASIS II processing system; 2) comparison with other orbit solutions, some of which were produced with independent data while other used the same data but different processing software or models; 3) external consistency checks that exploited the independent satellite height information provided by the on-board radar altimeter. These orbit quality assessment tests are described in detail in *Bertiger, et al.* [2].

The GIPSY/OASIS II software consists primarily of a GPS data editor, orbit integrator, measurement model generator, and filter/smoother. An automated executive ties the modules together producing daily orbit solutions unattended. The system typically produces a reduced dynamic orbit solutions for TOPEX/Poseidon within 2 days of acquisition of flight GPS data, using less than 6 CPU hours on an HP 735 workstation.

Ground Network Design

In addition to the post-processed high-accuracy GPS-based orbits for Topex/Poseidon, JPL experimentally produced over several weeks in the fall of 1994 (when anti-spoofing was on continuously) quick-look orbits for TOPEX/Poseidon using data from a subset (between 4 and 12 sites) of the ground network. The GIPSY/OASIS II software was operated through an experimental executive script automatically and continuously, producing near-real time TOPEX/Poseidon orbits within about 8 hours after midnight (for the day which ended at midnight). Since these quick-look orbits were determined later to be accurate to better than 1 meter even when propagated ahead in time 24 hrs, the demonstration actually produced sub-meter real-time knowledge of the satellite's three-dimensional position. In altitude, the orbit accuracy of the quick-look orbits was about 5 cm, with real-time knowledge better than 10 cm.

Other experimental versions of GIPSY/OASIS II have been used recently to test the capability to provide real-time meter-level knowledge of the GPS orbits, clock and SA delays, and ionosphere delays. Such products could be used in real-time navigation applications, such as the various systems being considered by the FAA for aircraft positioning.

Figure 2 shows orbit determination accuracy for TOPEX/Poseidon with various combinations of data from the flight and ground receivers. All accuracies are achieved using ground post processing except the fourth configuration from the left, which shows the accuracy possible using a filtering strategy on-board the Earth orbiter which uses on data from the flight GPS receiver. In addition to data showing accuracy dependence on the number of ground stations, Figure 2 also shows the accuracy that can be achieved by using only a small subset of the actual GPS data from the flight receiver (see rightmost bar). The next section will address a flight receiver architecture (among others) that can drastically reduce power consumption while incurring the remarkable small degredation in accuracy when only 5% of the GPS data are used.

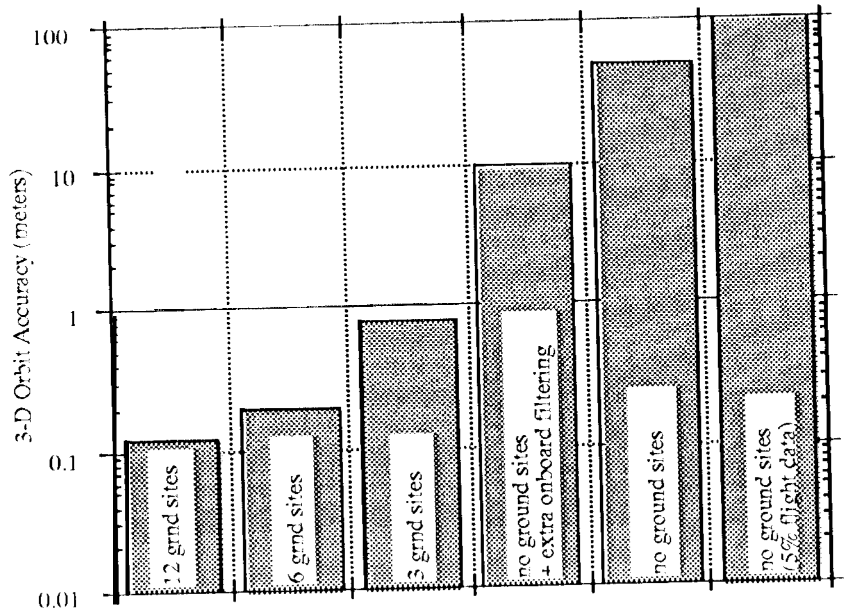


Figure 2: Comparison of TOPEX/Poseidon orbit accuracy for different strategies, with number of ground sites varying from 12 to zero. The fourth case incorporates extra onboard filtering to reduce errors from the fifth case, and the last (sixth case) includes only 5 min of data every 2 hrs (such a strategy could save power on a future mission)

Flight Receiver Architectures

GPS receivers in low-Earth orbit can offer the following advantages:

- enables autonomous navigation; eliminates need for ground processing for routine orbits (10-100 m orbits)
    - ground processing required only for Precise Orbit Determination (POD) (<10 m orbits)
- simplifies ground equipment requirements
    - require telemetry stations only; no doppler tracking required
    - does require access to GPS ground network data for POD
- provides the following signals to the rest of the spacecraft (in certain architectures):
    - one pulse per second timing signal (in certain architectures; ±200-1000 ns offset from GPS time)
    - frequency standard (in certain architectures; with phase noise and stability approximately equivalent to the GPS satellite clock ensemble)
- integrates of spacecraft uplink command receive function (in certain architectures)
- provides real-time platform attitude information (in certain architectures)
- "cost-free" atmospheric science opportunity with appropriately located supplemental antenna

Atmospheric Science with GPS

Addressing the last advantage first, JPL has great interest in the atmospheric limb-sounding science potential of high precision GPS receivers in low-Earth orbit and is actively pursuing several missions of opportunity. The GPS/MET instrument, funded by the National Science Foundation (NSF) is being developed by JPL under the direction of the University Consortium for Atmospheric Research (UCAR) and is scheduled to be launched by Orbital Sciences Corporation (OSC) on a Pegasus launch vehicle. An improved instrument is being funded by NASA and designed by JPL for the Danish spacecraft, Oersted. Both instruments are high precision GPS receivers that will collect global data which will be used to assess the utility of the GPS atmospheric occultation data type [7]. Figure 3 illustrates the GPS signal occultation of the Earth's atmosphere at various altitudes of interest. The time varying phase delay of the GPS signals will be recorded, downlinked and analyzed to produce global temperature and pressure profiles of the troposphere as well as ionospheric measurements. It would be advantageous to climate modeling or weather prediction to have as many occultation-capable receivers in orbit as possible; producing simultaneous, globally distributed atmospheric occultation data arcs. Since the occultation science requirements have led to a receiver architecture that can also offer most of the other listed advantages of GPS receivers in low-Earth orbit, it may be possible to include such receiver on large constellations of commercial satellites creating an potential source of vast science data.

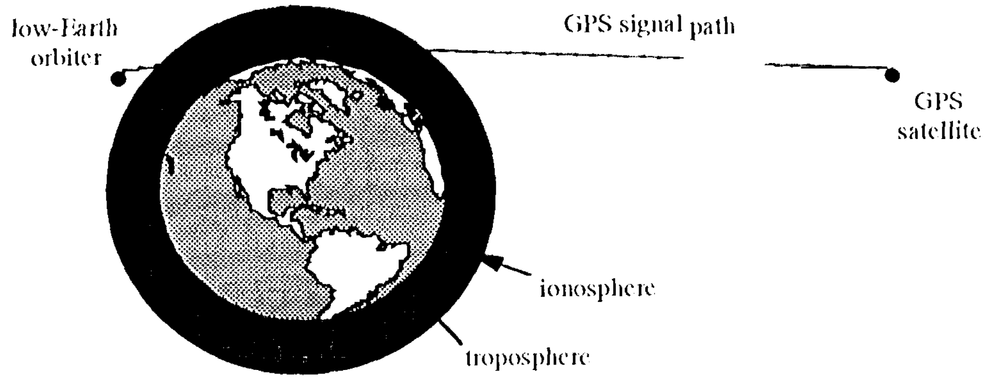


Figure 3: Atmospheric Occultation Geometry with GPS Satellite signals and LEO-based receiver

Configurable Receiver Architectures

Spacecraft and spacecraft instrument designers must give proper consideration to the continuum of options that seek to balance oft-conflicting performance and "cost" constraints. Typically, the "costs" are power consumption, mass, as well as actual cost of development, fabrication and test. JPL is investigating several GPS receiver architectures that are readily scaleable and offer a convenient way of trading off power/cost/mass constraints against navigation performance requirements. Performance can refer to real-time position accuracy as well as ultimate knowledge of the orbit gained through inclusion of ground network data and post-processing on the ground. The architectures presented herein address both definitions. They are intended to offer the space system designer a \\ridc-range of choice when inclusion of a flight GPS ltx'rive] is desired.

The simplest receiver architecture is illustrated in Figure 4. It offers simplicity and extremely low power consumption in exchange for reduced accuracy. This reduced power is achieved by only collecting very short lime samples of GPS data a few times per orbit (see Figure 2 for orbit accuracy degradation when sparse GPS data are wed). When the optional GPS processor is included, it would operate on these stored bits after each collection time, sequentially making measurements for each visible satellite in turn, and finally producing a point position. Otherwise, in exchange for even more simplicity and lower power consumption, the on-board processor can be eliminated and the stored GPS signal samples would be telemetered to the ground for post processing. This option reduces spacecraft autonomy, increases downlink bandwidth requirements, and introduces latency in orbit updates; all of which may be acceptable for spacecraft with severe power/mass limitations. In addition, this simple architecture can offer an low cost, backup mode to any flight receiver; at any time a short interval of antenna data can be captured and downlinked to the ground for analysis and health assessment. This architecture has not yet been demonstrated, but Performance has been verified in computer simulation (see text accompanying Figure ?).

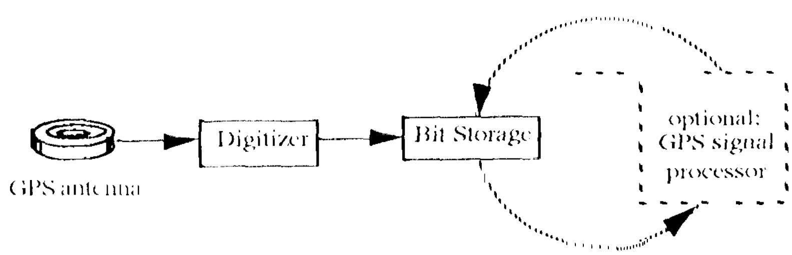


Figure 4: Functional Block Diagram of ultra-low power architecture

The highly configurable architecture is based on the geodetic quality, dual-frequency ground receiver developed by JPL. As seen in Figure S, the configurations offer a range of performance/power consumption compromises. The GPS/MET and Oersted flight receivers development experiences have led to the several of the key advances that enabled Ibis architecture.

[illegible]	Accuracy	[illegible] Consumption
Digitize, Store & Forward to Ground	[illegible]	[illegible]
[illegible]	~200 m	< 0.5 w (avg per orbit)
L1 Sparse Data & Fit to Orbit	~100 m	~1 w (avg per orbit)
L1 Continuous Data; point positions only	50-100 m	~4 w (continuous)
L1 Continuous Data; filter/fit to orbit	10-20 m	~4 w (continuous)
L1/L2 Continuous Data; ground processing	subdecimeter	6-8 w (continuous)

Figure 5: Range of receiver architectures with estimated performance and power consumption

The first key advance was the design of a satellite tracking channel that can process GPS signals both when *Anti-Spoofing* (AS) is turned on the by the DOD and when AS is off with the same signal processing hardware [8]. AS acts to encrypt the P-code broadcast by each satellite on L1 and L2 so that an authorized receiver (keyed so that the encryption is known) will not be "spoofed" by a fraudulent GPS signal broadcast from a source other than the GPS satellite. The second development was a receiver design which permits satellite tracking channels to track N satellites in dual frequency mode or N * 3 satellites in single frequency mode without hardware or software modification. While single frequency tracking reduces real-time positioning accuracy by 10 to 20 percent, the "cost" savings of a single receiver design for single or dual frequency may outweigh performance considerations for many applications. The third development is the inclusion of power management features in the receiver architecture. Specifically, the receiver that can selectively turn off various receiver components when not in use to reduce power consumption also well as vary the clock speed of the controlling microprocessor and the data rate of the GPS signal processor to meet a specific performance goals with the minimum power usage.

Clock Steering Capability

Properly equipped receivers, when not connected to an external frequency standard, can steer their internal oscillators using real time, in-receiver GPS solutions in order to keep the receiver clock offset from GPS time reasonably small (typically <200 ns in the presence of SA clock dither). This feature is known as "clock steering". Data processing from a high-Earth orbiter demonstration employing a ground network of receivers with "clock steering", showed formal errors on the estimates of the offset at each measurement time to typically be 0.1 to 0.2 ns [9]. These results are consistent with time-transfer capabilities demonstrated by *Dunn et al.* [10], whose results went further to show that GPS-based a clock drift (or frequency offset) measurement was also very small and agreed with, to within measurement errors, the drift measured using atomic standards and interferometric techniques in NASA Deep Space Network. The performance of GPS-based frequency offset measurement was also assessed for the GPS Demonstration Receiver (GPSDR) on TOPEX/Poseidon [11]. These studies suggest that one pulse per second (1 PPS) and frequency standard signals from a properly designed GPS receiver might considered as a possible substitute for a spacecraft's on-board frequency and time subsystem (FTS). Further study might include improved clock solution filtering techniques to improve GPS-steered receiver frequency standard in the presence of SA effects.

Integrated GPS/Telemetry Architecture

JPL is also developing a GPS receiver architecture that can offer significant power/cost/mass savings on an Earth orbiter by incorporating an uplink telemetry receiver within the GPS processor. This is accomplished in a recent lab demonstration at JPL (see Figure 6) by adding electronics to collect and down convert the telemetry bandpass and feed the digitized uplink into one of the GPS signal processing channels of a geodetic-quality GPS receiver.

With the GPS hardware channel acting as a command telemetry processor, software was then written and added to the receiver firmware to perform telemetry symbol synchronization and extraction and carrier phase acquisition and tracking. Telemetry bit streams of up to 2 kilosymbols per second (modulated with one of several standard methods) were extracted without special symbol extraction hardware. In addition, a precise phase/Doppler measurement was made of the uplink carrier signal that, in principle, can add strength to the on-board navigation solution when the location of the ground transmitter is well-known. If included in the uplink bandpass, a ranging signal could also be measured by such a receiver to add further strength (as well as validation value) to the on-board navigation solution.

The estimated specifications of an integrated GPS/Telemetry Receiver would reduce power and mass by a factor of two over a system using stand-alone telemetry receiver and GPS receiver.

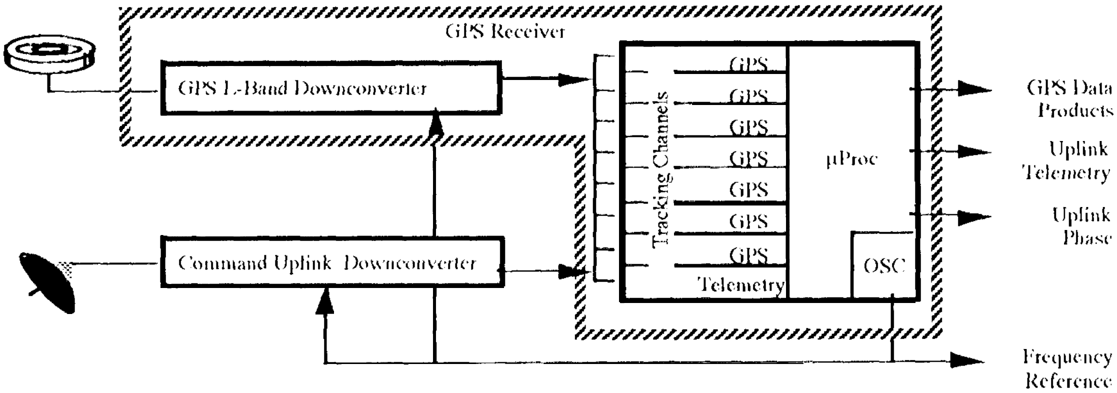


Figure 6: Integrated GPS/Telemetry receiver

Ground Systems for Data Communications

In the area of ground systems for data communications, JPL has recently demonstrated a potential Telemetry and Tracking System which consisted of a low cost (<$200k) weather satellite ground tracking station. The purpose of the system was unattended and continuous retrieval of science data telemetered from low-Earth orbiters. The demonstration showed that a workstation controlled the system can autonomously retrieve NORAD-published, km-level spacecraft ephemerides via commercial phone lines and automatically track and receive science telemetry from specified earth orbiters during overflights of the ground station location. The additional feature of this demonstration was the automatic distribution of the downlinked data to the personal computer of the cognizant Principal Science Investigator, also via commercial phone lines [12].

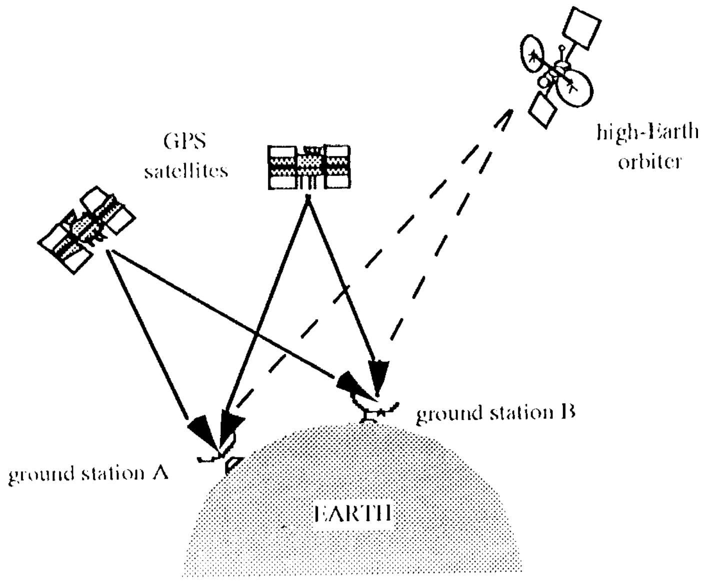
MEDIUM ALTITUDE EARTH ORBITER APPLICATIONS

The "upwards-looking" GPS configuration employed for low-Earth orbiters is suitable only for orbits up to about 3000 km. Above this altitude GPS signal visibility from a zenith pointing antenna begins to degrade and it becomes advantageous to employ an additional antenna in a "down-looking" configuration [13]. For the down-looking geometry, the orbiting user directs the receiving antenna down towards to Earth and tracks the GPS satellites located on the far side (GPS satellites broadcast a beam which is slightly wider than the angle which the Earth subtends.). This technique (for the 3000-8000 km altitude range) has not yet been demonstrated in an actual flight test and it might require directional and steerable flight antennas (in contrast to the usual fixed hemispherical, zenith looking, antenna). A magnified atmospheric distortion effect is also expected. Finally, GPS signals will be weaker since they must travel a farther distance and the data would be sampled from the edge of the GPS broadcast beam pattern.

HIGH EARTH ORBITER TECHNOLOGIES

At altitudes above 8,000 km, the visibility of the GPS signals degrades rapidly and the geometry becomes increasingly poor as the user satellite moves away from the Earth, regardless of the antenna pointing configuration. A need for precise positioning services at these extremely high altitudes exists among the geosynchronous spacecraft orbiting at an altitude of 30,000 km. It is for these and higher altitude applications (up to 150,000 km) that JPL has developed GPS-like tracking (GLT), illustrated in Figure 7, an approach which exploits GPS in a decidedly different way than the techniques outlined above [9].

The GLT approach for high-Earth orbiters replaces the usual flight GPS receiver on the user spacecraft with an Earth-pointing transmitter beacon whose signal structure is such that it can be phase tracked, along with GPS signals, using a globally dispersed network of "enhanced" ground GPS receivers. The configuration illustrated in Figure 7 also shows the similarity between high-Earth orbiter and GPS satellite orbit determination. In principle, the accuracy of high-Earth satellite orbits should approach that of GPS satellite orbit determination (routinely determined by JPL and several other analysis centers to better than 50 cm). In the GLT technique, precise GPS tracking on the ground serves to calibrate media delays, synchronize clocks between stations, and account to various geophysical parameters (like station coordinates).



The concepts of interferometric phase tracking of geosynchronous orbiters and using GPS to assist in their orbit and trajectory determination have their heritage in deep space tracking techniques and were developed and refined in the mid 1980's by JPL scientists [15,16]. Recent analysis has suggested that meter level orbit accuracies can be achieved at altitudes up to 150,000 km using a globally spread network of combined beacon/GPS tracking stations [3]. First demonstrated earlier this year using NASA's Tracking and Data Relay Satellite System (TDRSS), GLT data yielded geostationary satellite orbits with an accuracy of 50 meters in total position [9]. These results however, were consistent with previous analysis since, due to the small footprint of the beacon, the three ground stations employed in the demonstration were located within 1000 km of one another, weakening the geometric strength of the solution.

TDRSS, whose space segment includes 5 geosynchronous orbiters, is used by NASA to support positioning and data relay activities and accurate near real-time positioning of the TDRSS spacecraft is fundamental to proper operation. In the case of the Tracking and Data Relay Satellites (TDRS), the beacon tracked in the ground stations is present whenever the system is servicing user spacecraft and determination of the TDRS orbits using GLT can be performed without disruption of user services (a characteristic not shared by the current operational orbit determination system, Bilateration Ranging Transponder System (BRTS), against which the GLT results were compared).

Once again, the data analysis was carried out using a augmented version of the GIPSY/OASIS package of modeling and estimation algorithms. The ground tracking stations consisted of dual-frequency, geodetic quality GPS receiver "enhanced" by JPL with special phase-tracking software and electronics necessary to receive and down convert the Tracking and Data Relay Satellite (TDRS) the existing Ku-band (13.731 GHz) spacecraft-to-ground link (SGL), which served as the beacon signal. The next few sections will examine more closely, and consider future improvements to, the data analysis strategies and "enhanced" ground receiver design as they apply to orbit and trajectory determination for high-Earth orbiters.

Data Analysis Strategies and Implementation

Nandi et al. [17] proposed a method which uses a GLT network and relies on monitoring only the station-differenced carrier phase with integer ambiguities and biases left unresolved. These so-called short baseline differenced carrier phase (SBAΦ) measurements determine the *change* in plane-of-sky position of the user spacecraft. When included in a dynamical orbit determination, the SBAΦ measurements can determine 5 of 6 components of the spacecraft state vector. The longitude of the orbit- or the satellite's down-track position in inertial coordinates- is poorly determined; moreover, the orbit solution is somewhat sensitive to mismodeling of forces such as solar radiation pressure [9]. To combat these problems, a few well calibrated range measurements were needed.

The unified TDRS/GPS orbit solutions were performed using the GIPSY/OASIS II software. The solution strategy, with a few exceptions, is the same as that employed for routine processing of GPS for the International GPS Service (IGS) global network [18]. One notable difference is the way in which the TDRS phase data were modeled. The TDRS phase data were modeled as 3-way measurements (i.e. 2 legs and 3 participants). Although it is instructive to think of TDRS as the originator of the signal (in the manner of GPS), this is not strictly correct. The signal originates at White Sands Ground Terminal (WSGT) in New Mexico, and is transmitted to TDRS which serves as a "bent-pipe" transponder, redirecting the signal to the ground. It follows that the TDRS clock offset is not solved for in the orbit determination procedure, but rather it is appropriate to solve for the offset of the master frequency generator on the ground at WSGT. This modeling ensures that the Doppler signature from the uplink is handled properly, i.e. it is not incorrectly absorbed in the TDRS clock solution. The range data from WSGT were modeled as simple 2-way measurements [9].

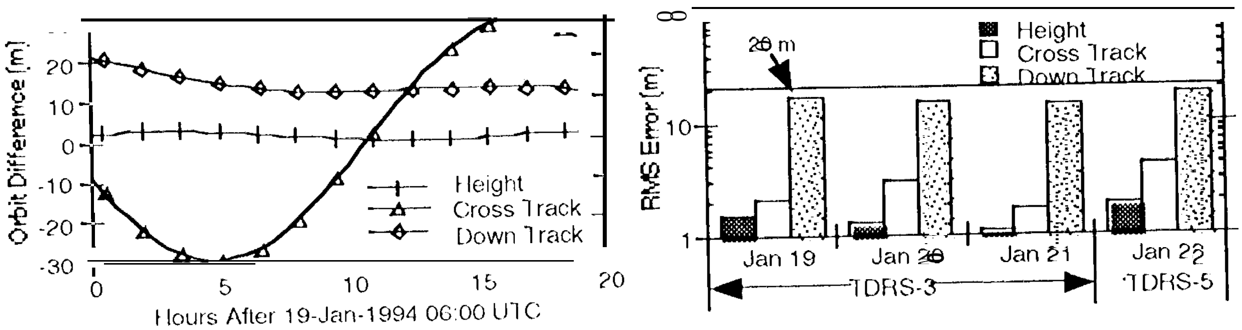


Figure 8a,b: a) TDRS-3 inertial orbit differences between GLT and BRTS (from Goddard Space Flight Center) orbits for January 19, 1994. The RMS differences in height, cross track, and down track are 1.6 m, 22.4 m and 14.2 m respectively. b) Bar graph showing RMS formal errors of GLT-based TDRS orbit solutions. The arcs vary between 18 and 20 hours in length.

The comparisons between the GPS-based local (regional) network solutions and the global BRTS solutions shown in Figure 8 indicate rms agreement at the level of about 25 meters or better. It is possible that the GPS-based orbits are, in fact, more accurate than this, but at the present time the BRTS orbits are the best that are available for intercomparison. Note also that for the above solutions, the White Sands range bias was calibrated with the BRTS orbit, so the down track results show internal consistency (precision) rather than an independent measure of accuracy.

"Enhanced" Ground Receiver Design

Use of the GLT and SBAΦ techniques for precise TDRS orbit determination applications is further challenged by the narrow beamwidth of the TDRS SGL: the down link illuminates only a limited region of the southwestern US. surrounding the TDRS Earth station at White Sands, New Mexico. The size of the SGL footprint precludes the use of long, continental baselines for orbit determination. Since the angular sensitivity of the tracking measurements are proportional to the baseline length, good performance with short baselines requires extremely tight control of delay errors. Indeed, all the potential sources of delay error in a short-baseline tracking scenario can be measured with GPS: a) *Clock synchronization/time transfer:* Routine processing of GPS data for the IGS are providing clock synchronization at tracking stations dispersed around the globe to better than 1 ns [10,19]. b) *Station coordinates:* Geocentric station coordinate solutions accurate at the cm level are generated routinely [1]. c) *Atmospheric delays:* Zenith wet troposphere delays can be measured in a variety of conditions with an accuracy that rivals that achieved by radiometers [20]. The dual-frequency nature of the GPS signal also allows calibration of the ionosphere delay, but this effect is quite small for the 13.731 GHz SGL from TDRS.

In addition to providing above calibration parameters 101111' TDRS tracking system, the GPS ground receivers also perform the precise phase tracking of the TDRS Ku-band spacecraft-t o-ground link. Figure 9 illustrates this capability, which was added to an existing geodetic-qua lity GPS receiver by the development and inclusion of additional electronics and softwa re. The electronics consisted of a small, Ku-band horn antenna (opening dimensions 1 7 X 14 cm) and a Ku- to L-band downconverter, both developed at JPL. The TDRS SGL, after translation to L-band, was power combined \\ 'ill) the GPS L-band signal. The relative power levels of the two signals were set such that Sigtlal-lo-Noise Ratio losses we re minimized. In addition, the receiver was augmented with software, also developed by JPL, which measures and records the phase of the TDRS SGL with the same sub-mm precision and receiver time-stamp as GPS carr icr phase measureme nts. This ability of the receiver architecture to permit integration of SGL tracking, coupled with the powerful calibration features of precision GPS tracking, leads most significantly to the simplicity of the TDRS ground stations.

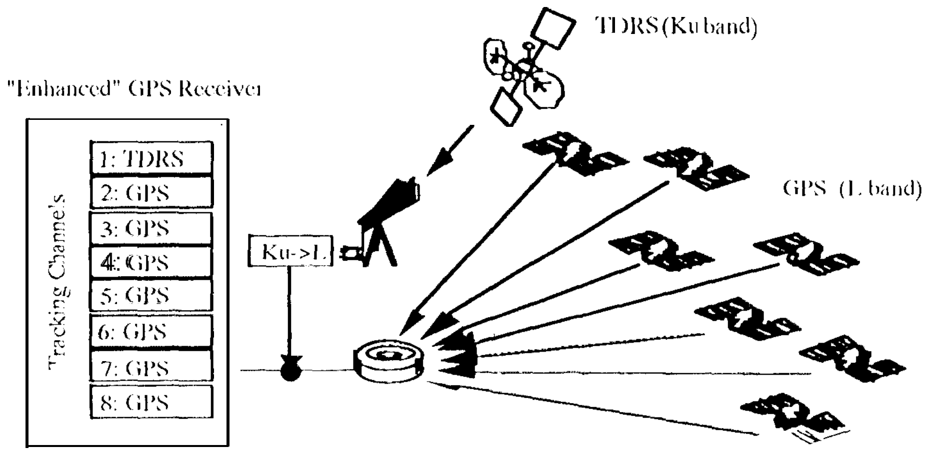


Figure 9: Component diag ram for the GLT ground tracking station for TDRS, including the "enhanced" GPS receiver which simultaneously tracks TDRS along with GPS satellites. For the TDRS SGL, which is at 13.731 GHz, a small separate antenna with down converter wa s added.

Another key feature of the GLT tracking stations used for the TDRS demonstration is the abi lity to remotely monitor operations and download data in an automatic, unattended fashion. The long term effectiveness and reliability of such a tra cking station has already been demonstrated in the autonor nous and continuous operation of the IGS network of over 50 globally distributed GPS tracking stations [18]. The IGS tracking stations are identical to the TDRS demonstration tracking stations except that they lack the TDRS specific antenna and downconverter ha rdware. They, in fact, alre ady contain the software necessary to track a high-Earth orbiter SGL. This software, however, is not invoked during normal GPS-only operation.

SUMMARY

JPL's technologies for real-time and post processed orbit determination for Earth orbiters of various altitudes have been outlined in this paper. Use of dual band GPS data from the TOPEX/Poseidon low-Earth orbiter flight instrument and incorporation of the reduced dynamic technique can routinely and automatically produce orbits accurate to a few centimeters in altitude and 10-20 centimeters overall. A demonstration with the TDRSS constellation showed that the GPS-like tracking data, combined with range data and GPS data acting to calibrate a number of critical parameters, produces geostationary orbits with better than 50 meter accuracy. In addition, JPL's development of a high precision receiver to make atmospheric radio occultation measure ments has led to a configu rable receiver architecture which could offer a diverse choice of flight receivers to the space system designer. Depending on the altitude of the satellite, on the complexity (and cost) of the system, and on the time delay in producing results, GPS-based tracking syste ms can provide orbit knowledge at the cm-level or at the level of a few hundreds of meters. Experiments recently carried out at JPL have, in fact, demonstrated these capabilities for satellites in low-Earth to geostationary altitudes, wi th a wide breadth of processing strateg ies ranging from detailed post-fit analysis to complete automation. These experiments have included the development of new hardware and software technology which are now suitable for either direct transfer to industry or further co-development with commercial partners.

Most of the techniques have been possible due the flexibility and power of the GIPSY/OASIS II software package developed by JPL over the past decade as well as the geodetic quality GPS receivers designed by JPL. The ability to employ these tools on diverse applications has led to the application of GPS-based tracking techniques to a wide-ranging set of Earth orbiter applications.

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